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DETERMINATION OF HEAT FLUX LAYOUT IN THE MOULD FOR CONTINUOUS CASTING OF STEEL

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The paper deals with research of the heat transfer in the mould of continuous casting and the thermal boundary condition determination using combination of measurement and the inverse technique of numerical simulation. An average heat flux in the mould is calculated from measured parameters of mould cooling water. Layout of the heat flux at the mould working surface is derived by the original experimental and numerical simulation procedure, which is based on measuring temperatures in the mould walls and solving a numerical inverse problem including stress and shrinkage, using the software package Procast. A database of the heat flux layouts was built for various values of casting speed and steel chemical composition for purpose of determination the boundary condition for on-line modelling.

Key words: continuous casting of steel, mould, heat removal, heat flux, boundary condition

Određivanje raspodjele toplinskog toka u kristalizatoru za kontinuirano lijevanje čelika. U članku je istražen prijenos topline u kristalizatoru za kontinuirano lijevanje i određivanje toplinskog graničnog uvjeta upotrebom kombinacije mjerenja i inverzne tehnike numeričke simulacije. Prosječni toplinski tok kristalizatoru je izračunat iz mjernih parametara rashladne vode za kristalizator. Raspodjela toplinskog toka na radnoj površini kristalizatora je dobivena originalnim eksperimentalnim postupkom i numeričkom simulacijom, a zasiniva se na mjerenju temperatura u stjenci kristalizatora i rješavanju numeričkog inverznog problema uključujući naprezanje i stezanje koristeći programski paket Procast. Baza podataka o raspodjelama toplinskog toka je formirana za različite vrijednosti brzine lijevanja i različite kemijske sastave čelika u cilju određivanja graničnog uvjeta za on-line modeliranje.

Ključne riječi: kontinuirano lijevanje čelika, kalup, odvođenje topline, toplinski tok, granični uvjet

INTRODUCTION

Monitoring and simulation of the mould thermal work during continuous casting is a technique necessary for achieving quality and safe production [1 - 5]. There is a necessity of determining the momentary boundary condition for on-line thermal numerical model, which is usually a part of caster's monitoring and diagnostics system. Thermal numerical models for an operational usage usually include the strand without the mould itself and often use heat flux on the strand surface as a boundary condition. The integral of heat flux through the working area of mould walls is equal to the total heat flow from mould walls to the cooling water which can be simply derived from routinely measured parameters of the cooling water.

To get more precise simulation results, the layout of heat flux on the mould working surface is needed as a boundary condition [6, 7]. The heat flux layout is rarely known, mainly near mould corners, and it is not an easy task to obtain it.

Measuring of heat flux by pairs of thermocouples was developed for an experimental purpose, but the technique is impractical for the long term operational use because of technical and financial demands. Similar results have been obtained by application of smaller number of temperature sensors in the mould walls in combination with an advanced off-line modelling using the software Procast. The research has been carried out on casters of formats 150 × 150 mm and 200 × 200 mm.

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AVERAGE HEAT FLUX MEASURING

The average heat flux q_m in the mould walls can be determined from measured cooling water temperatures and flow rate using the following equation

$$q_m = \frac{1}{A_m} \cdot \rho \cdot Q_w \cdot (c_{p,2} \cdot t_2 - c_{p,1} \cdot t_1) \qquad (1)$$

where A_m / m^2 is the area of mould working surface, ρ / kg·m^{-3} is water density at the position of flow rate sensor, Q_w / m^3·s^{-1} is water flow rate, t_1, t_2 / °C are temperatures of inlet and outlet cooling water, $c_{p,1}$, $c_{p,2}$ / J·kg^{-1}·K^{-1} are mean specific heats of water at temperatures t_1, t_2.

According to the experimental data analysis, the average heat flux depends mainly on the casting speed and on chemical composition of the steel, apart from the mould dimensions and taper, type of the casting powder etc.

It follows from the long term in plant measurements that the average heat flux in the mould of the format 150 × 150 mm varied between 1,3 and 2,1 $MW \cdot m^{-2}$ while in the mould 200 × 200 mm it ranged between 0,9 and 1,8 $MW \cdot m^{-2}$. The length of the mould 150 × 150 mm was 1 m while the casting speed varied between 1,9 and 2,9 $m \cdot min^{-1}$. The length of the mould 200 × 200 mm was 0,7 m and the casting speed varied from 0,3 to 1,2 $m \cdot min^{-1}$ during the experiment.

The global trend of heat flux in the mould shows its rise with increasing steel carbon content and with growth of casting speed, with the exception of particular steel grades, e.g. low carbon steels [6].

Heat flux in the real mould varies along the mould length and width and drops mainly near the corners. The heat flux layout can be compiled from the average value using additional information either from the matrix of thermocouples in the wall or using off-line simulations results described below.

HEAT FLUX LAYOUT MEASURING BY PAIRS OF THERMOCOUPLES

Heat flux in the mould walls was measured by direct method using pairs of thermocouples, placed at different distances from the work surface, see the Figure 1. The distance difference Δx is critical for heat flux calculation accuracy. The following equation is used for the heat flux calculation

$$q = \frac{t_{m1} - t_{m2}}{\frac{\Delta x}{\lambda}} \quad (2)$$

where t_{m1}, t_{m2} / °C are temperatures measured by the pair of thermocouples, Δx / m is a distance of thermocouples and λ / $W \cdot m^{-1} \cdot K^{-1}$ is heat conductivity of the mould.

Pairs of thermocouples were installed during the experimental measurement at 4 vertical lines and 5 horizontal levels in each wall of the mould of the format 200 × 200 mm. In total there were 160 thermocouples installed in four walls, which allowed calculation of heat flux in 80 positions, i.e. 20 positions in each wall. In the Figures 2 and 3 there are charts of heat flux layout on the working surface in dependence on the thermocouple position in the horizontal and vertical directions. The Figure 2 corresponds to the casting speed 0,4 $m \cdot min^{-1}$ and the Figure 3 shows the result for the speed 0,7 $m \cdot min^{-1}$. The steel carbon content in both cases was 0,15 wt.%. The average heat flux at casting speed 0,4 $m \cdot min^{-1}$ was 900 $kW \cdot m^{-2}$ and at the speed 0,7 $m \cdot min^{-1}$ it was 1500 $kW \cdot m^{-2}$.

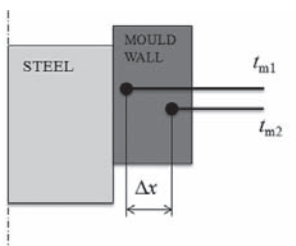

Figure 1 The pair of thermocouples in the mould wall

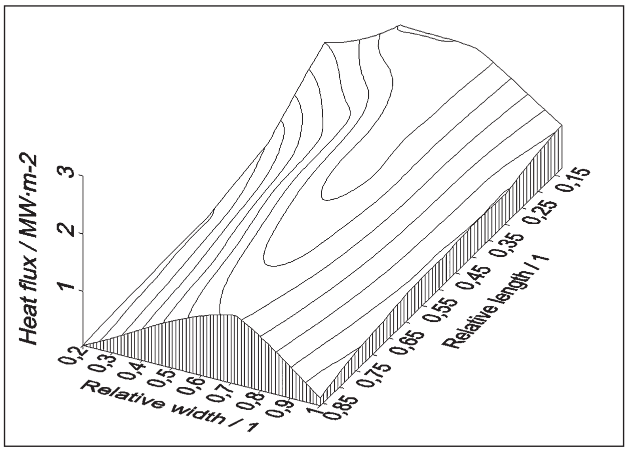

Figure 2 Measured layout of heat flux in the mould wall at casting speed 0,4 m·min-1 (format 200 × 200 mm)

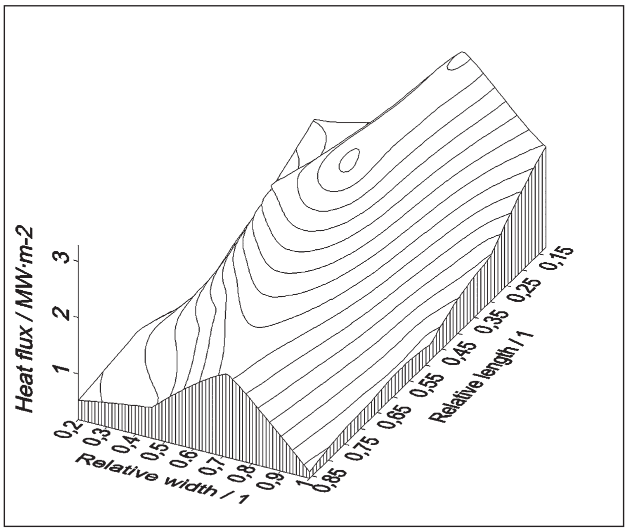

Figure 3 Measured layout of heat flux in the mould wall at casting speed 0,7 m·min-1 (format 200 × 200 mm)

Several various techniques of thermocouple probe design were tested. The first way was welding the constantan wire directly on the bottom of the hole in the copper wall by an electric spark which formed the thermocouples of type T. Better results were obtained with thermocouples of type E fixed in a cylindrical copper plug, which was forced on into the hole drilled into the wall. More than a hundred of heats at various casting parameters and steel grades were measured during the experimental work. The technique is not suitable for permanent application at the plant because of its technical and financial demands.

To illustrate the heat flux drop in the transversal direction, the ratio of the heat flux near corners to the heat flux in the middle of the wall was evaluated. The ratio is shown in the Figure 4 in dependence on the longitudinal position for two various casting speeds. Heat flux near corners drops down to 16 % of the heat flux in the middle of the wall.

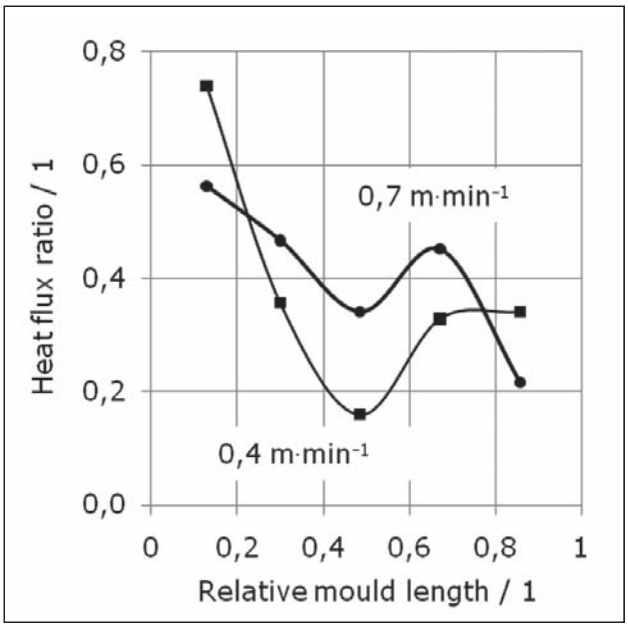

Figure 4 The ratio of measured heat flux near corners to heat flux at the wall centre (format 200 × 200 mm)

DETERMINING HEAT FLUX LAYOUT BY INVERSE SIMULATION

Without the temperature sensors in the mould, the heat flux layout can be determined by numerical modelling. An inverse simulation technique was used and verified at the format 150 × 150 mm. Only the knowledge of the total heat flow to the cooling water is necessary, although for a limited time there were installed five single thermocouples at the longitudinal axis in each wall for the purpose of model verification, see Figure 5.

The 3-dimensional model must include the mould and the strand, see the Figure 6. A gap between the shell and the mould is filled with the lubricant and gas. The gas gap forms due to the shell shrinkage mainly in the lower part of the mould where the shell is strong enough to resist the static pressure of the liquid metal.

The gas gap increases thermal resistance of the gap and consequently causes dropping of local heat flux. Heat flux from the strand surface to the cooling water can be expressed by the equation

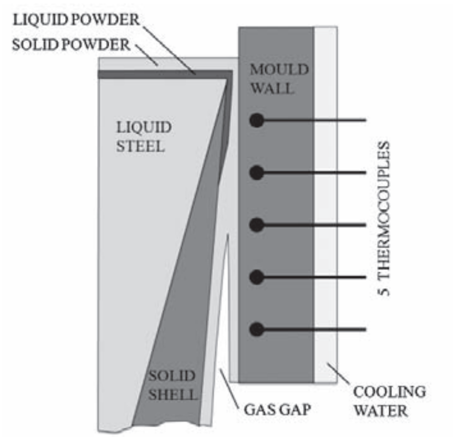

Figure 5 The schema of the mould wall and the strand

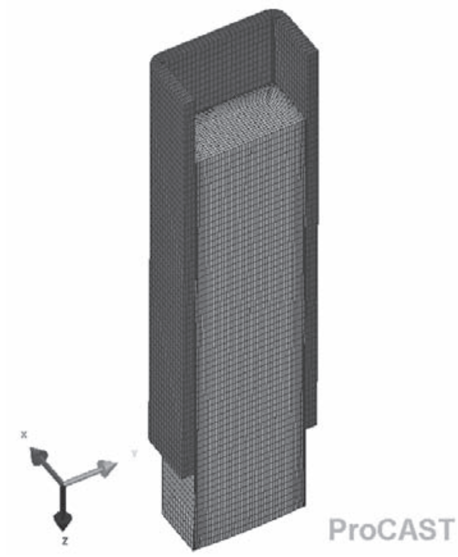

Figure 6 The 3-dimensional model of the mould

$$q = \frac{t_s - t_w}{\dfrac{1}{k_L} + R_g + \dfrac{b}{\lambda} + \dfrac{1}{\alpha_w}} \tag{3}$$

where t_s / °C is strand surface temperature, t_w / °C is cooling water temperature, k_L / W·m^{-2}·K^{-1} is heat transport coefficient through the lubrication layer, R_g / m^2·K·W^{-1} is thermal resistance of the gas gap, b / m is mould wall thickness, λ / W·m^{-1}·K^{-1} is heat conductivity of the mould wall, α_w / W·m^{-2}·K^{-1} is heat transfer coefficient between the mould wall and the cooling water.

The software package Procast is able to simulate the shell thermal shrinkage, in addition to the temperature field, as a coupled problem. The gas gap thickness is calculated as well. The Procast has a feature of automatic correction of thermal boundary condition according to the calculated gas gap thickness.

The thermal boundary condition is a complex condition which includes the heat transport coefficient k_L from the shell to the mould through the lubrication layer and the heat transmission coefficient α_w from mould wall to the cooling water by forced convection. The initial value of k_L is estimated by a simple 1-dimensional thermal model, at first considered as constant for the whole mould. The value of α_w is calculated using a criteria equation from known cooling water temperature and velocity, the cooling channel size and the mould surface temperature.

During the simulation, as soon as the Procast algorithm identifies the gas gap existence, the heat resistance R_g is automatically added to the boundary condition. After obtaining a steady temperature field, the integral of heat flux on the mould working surface is evaluated and compared with the known value of heat flow to the cooling water P_w. The next step is a correction of the average heat transmission coefficient k_L and repeating the simulation until the integral of heat flux equals to the heat flow P_w.

The more precise results were obtained when coefficient k_L was considered not constant but dependent on

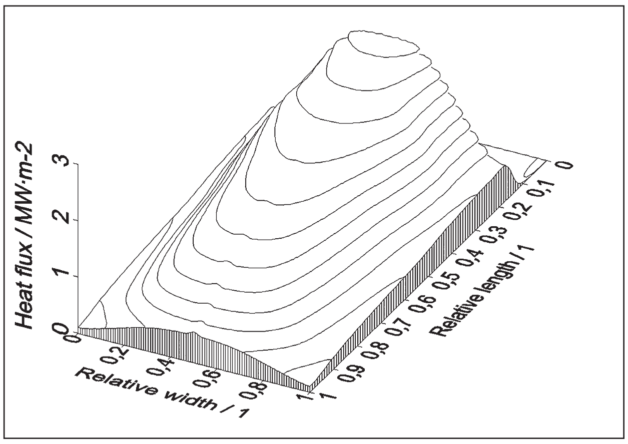

Figure 7 Simulated layout of heat flux in the mould wall for casting speed 1,8 m·min-1 (format 150 × 150 mm)

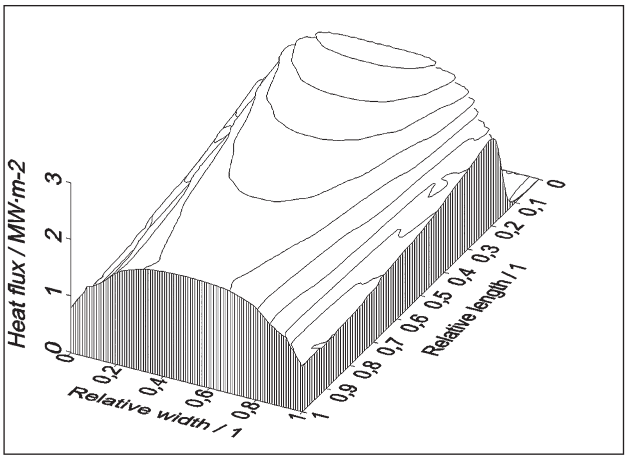

Figure 8 Simulated layout of heat flux in the mould wall for casting speed 3,2 m·min-1 (format 150 × 150 mm)

the mould position. The iteration process in this case is generally more time demanding. The minimum sum of least squares of differences between simulated and measured temperatures in the mould walls is used as an additional criterion for optimization.

The simulated layout of heat flux on the working surface in dependence on coordinates for the casting speed 1,8 m·min^{-1} is presented in the Figure 7 and similarly the Figure 8 shows the layout for the speed 3,2 m·min^{-1}. The steel carbon content was 0,73 wt.% in both cases. The average heat flux at casting speed 1,8 m. min^{-1} was 1,4 MW·m^{-2} and 2,1 MW·m^{-2} at the speed 3,2 m·min^{-1}.

The ratio of heat flux near corners to the heat flux in the middle of the wall in dependence on longitudinal position was evaluated for the both values of casting speed. The chart is shown in the Figure 9. Heat flux near corners drops down to 20 % of the value in the middle of the wall.

Number of simulations has been carried out in order to develop a database of reference boundary conditions. The simulated heat flux layouts have been approximated by polynomial and spline functions, separately for each wall, as relative values to the average heat flux which is calculated on-line from cooling water parameters. The database contains approximation functions

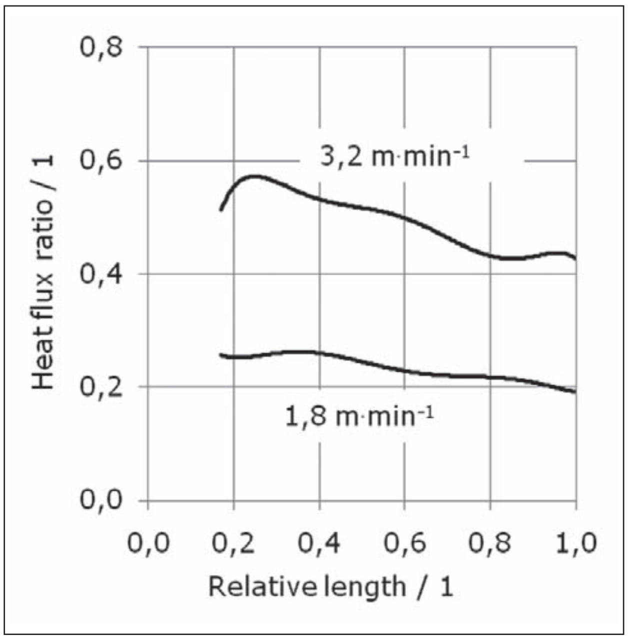

Figure 9 The ratio of simulated heat flux near corners to heat flux at the wall centre (format 150 × 150 mm)

parameters for typical steel grades and for five values of casting speed.

CONCLUSION

A necessary precondition for simulations of the continuously cast strand temperature field is the knowledge of the boundary condition in the mould. The direct method based on measurement of temperatures in the mould wall as well as the inverse simulation technique using software package Procast was developed. The database of approximation functions parameters for heat flux layout determination was created for further usage in numerical models.

Acknowledgments

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Note: The responsible translator for English language is Jiří Szymutko, Pasecká 282, Albrechtice u Českého Těšína, Czech Republic.